Local probing of thermal properties at submicron depths with megahertz photothermal vibrations

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(Received 26 August 2002; accepted 2 December 2002)

We demonstrate the imaging of buried features in a microstructure—a tiny hole in an aluminum thin film covered by a chromium layer—with nanometer lateral resolution using a transient temperature distribution restricted to within ~0.5 μm of the sample surface. This is achieved by mapping photothermally induced megahertz surface vibrations in an atomic force microscope. Local thermal probing with megahertz-frequency thermal waves is thus shown to be a viable method for imaging subsurface thermal features at submicron depths.
[DOI: 10.1063/1.1539906]

The scanning thermal microscope, making use of a probe tip composed of an ultrasmall temperature sensor or resistive heater, has allowed the local imaging of thermal properties on lateral length scales down to ~25 nm.[1,2] Of particular interest in this field are techniques in which a transient temperature distribution is used. Thermal waves are sensitive to the heat capacity as well as the thermal conductivity, providing an extra source of contrast. Moreover, unlike the case for varying elastic fields, the intrinsically damped thermal wave propagation can be controlled through the oscillation frequency f: the thermal penetration depth—essentially the thermal diffusion length—decreases with increasing frequency as $1/f^{1/2}$, and so it is advantageous in microscopy with thermal waves to work at high frequencies in order to achieve a high spatial resolution. Because of the ongoing trend toward device miniaturization with features less than ~100 nm in size, local probing of thermal modulation phenomena is an area of paramount importance.

One approach that combines oscillating (that is, ac) temperature fields and local probing is based on the use of a modulated heat source in the tip.[3,4] Although useful images sensitive to thermal diffusivity have been obtained, such experiments are difficult to interpret because the depth resolution is often strongly influenced by near-field thermal effects governed by the probe size and tip–sample thermal resistance rather than by the modulation frequency.[2] A different approach that avoids this complication is based on the local probing of thermal expansion: subsurface periodic resistive heating[5,6] or chopped optical radiation[7–9] generate surface vibrations that can then be mapped to a lateral resolution of a few nanometers in standard atomic force microscope (AFM) or scanning tunneling microscope configurations. This produces additional contrast through the thermal expansion coefficient. However, such imaging with these ac local thermal probing techniques so far has been done at frequencies ≲100 kHz, corresponding to a thermal penetration depth in insulators that is greater than ~1 μm. This is still too low a frequency for optimal ac thermal imaging of thin films or structures of thickness in the ~100 nm range or below. There is, therefore, a pressing need to extend such ac local thermal imaging to significantly higher frequencies.

Toward this end, we make use of a technique that we term optical heterodyne force microscopy (OHFM), involving the local probing of photothermally induced ultrasonic surface vibrations. Figure 1 shows the experimental setup, based on a commercial AFM (TM Microscopes, CP-M). We illuminate a region of the sample surface $D \sim 2$ μm in diameter directly below the tip at normal incidence with MHz chopped light (at $f_1 = 4.223$ MHz) of typical average power $P = 0.7$ mW and wavelength 830 nm.[10] We therefore choose a transparent silicon nitride cantilever[11] (of spring constant 0.1 Nm^{-1}) and tip (of radius 20 nm). In addition to a dc

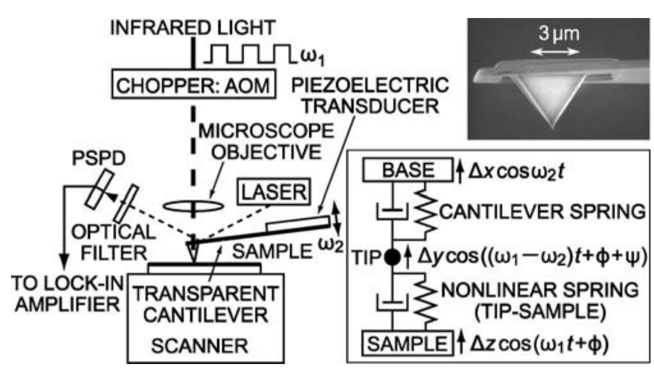

FIG. 1. Schematic diagram of the experimental setup and model used for optical heterodyne force microscopy. PSPD means position-sensitive photodiode and AOM means acousto-optic modulator. In the model, the phase ψ is the part of the phase not related to the phase ϕ of the thermal expansion. Also shown is a scanning electron micrograph of the tip.

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